Large-Eddy Simulations of Tropical Convective Systems, the Boundary Layer, and Upper Ocean Coupling

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LONG-TERM GOAL

Improve operational numerical weather prediction (NWP) models to more accurately simulate the interaction of tropical deep convection and atmospheric and oceanic boundary layers.

OBJECTIVES

Investigate tropical convection and upper ocean circulations on scales from 100 m to 200 km. Elucidate specifically how the ocean mixed layer responds to forcing from atmospheric convection such as wind and precipitation, and thus how surface fluxes depend on the history of convective events. Perform high-resolution coupled atmosphere-ocean numerical model simulations, whose fidelity is a benchmark for operational models and parameterizations. Insights gained from these simulations will be used to improve parameterizations used in operational scale models, and to refine hypotheses in collaboration with investigators working on observational field studies in the Indian and West Pacific Oceans.

APPROACH

Intraseasonal variability in the tropics is dominated by the Madden-Julian Oscillation (MJO), which generates large-scale variability in the structure and organization of deep convective cloud systems. MJO events consist of multiple scales of convective activity, from single kilometer-sized cells to circulations encompassing half of the tropical Pacific. Key factors for tropical convection include sea-surface evaporation and large-scale atmospheric moisture convergence, which both depend on sea-surface temperature and wind speed. Most numerical models do not resolve turbulent and convective scales, nor do they simulate the MJO accurately. We investigate how convection during the active

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phase of MJO affects and interacts with the ocean mixed layer. We conduct large eddy simulation (LES) of organized convective systems, which resolve boundary layer eddy scales to mesoscale convective towers. These numerical simulations reveal how atmospheric convection alters air-sea fluxes and the ocean boundary layer, and will help refine hypotheses on coupling between the ocean and atmospheric boundary layer during MJO events. Processes on these scales are gaining importance in operational NWP models as the realism of convection increases along with model resolution.

WORK COMPLETED

Research during the fourth year of this project has focused on analyzing data from the DYNAMO cruise conducted in the fall of 2011 and performing large-eddy simulation (LES) experiments of tropical convection initialized using soundings derived from field program. We have modified the LES model to include a variable grid near the surface for better resolution of cold pool systems. Analysis methods were also developed to identify cool pool events in the ship observations and form composite averages of the measured covariance fluxes as well as bulk calculated values for cold pool events.

RESULTS

We are particularly interested in air-sea interactions and their relation to intraseasonal variability. How does the exchange of momentum and radiative, sensible, and evaporative heating anomalies between the ocean and atmosphere affect the evolution of the MJO? We will identify convective and air-sea interaction processes that contribute to the genesis and propagation of MJO convective anomalies. Guided by the DYNAMO observations and large-eddy simulation of deep convective systems, we find a vital connection between deep convection and the surface heat and moisture fluxes through *atmospheric cold pools* generated by evaporating hydrometeors. In this report we focus on intraseasonal anomalies of surface meteorology, sea surface temperature (SST) and air-sea fluxes; and intraseasonal changes in mesoscale cold pools and gust fronts observed in DYNAMO.

In the central Indian Ocean at the equator, 80°E, multiple measurements from the *R/V Revelle* observed two, perhaps three, MJO active convective events. We identify these events in ship observations of SST, solar radiation, and zonal wind *in situ*, from rawinsonde atmospheric profiles, and radar precipitation statistics. Large-scale context and eastward intraseasonal propagation are identified from satellite observations of the Indian Ocean basin. We measure surface meteorology and radiative fluxes on 1-minute time scales, and turbulence fluxes are continuously estimated from covariance between 3-dimensional velocities, temperature and humidity sampled at 10 Hz. We also measure coherent and turbulence structures with the NOAA Doppler cloud radar and high-resolution Doppler lidar (HRDL).

Three-dimensional large-eddy simulations (LES) of atmospheric convection at comparable resolution to the ship observations show the connection between vertically extensive precipitating cumulus clouds and mesoscale air-sea interaction at the surface. Cold pools, cool gust fronts measured at the surface, comprise much of this interaction. Statistics of cold pools are generated from ~200 observed fronts and temperature recoveries. Turbulence fluxes are composited throughout the passage of the cold pools.

Time series (Fig. 1) show intraseasonal SST rising from excess sunlight (and weak wind) during suppressed phases, and falling during the convective phases of the MJO, when clouds block sunlight reaching the surface. Net surface flux becomes negative during brief periods with suppressed diurnal warming of SST and 1-3°C negative T_{air} anomalies lasting tens of minutes.

Model results show that narrow (<1 km) negatively buoyant downdrafts from evaporation of hydrometeors form cold pools with temperature and wind anomalies similar to the surface observations (Fig. 2). Precipitating freshwater is mixed into the ocean by wind stress from the gusts. LES experiments suppressing hydrometeor evaporation eliminate cold pools and demonstrate radically different air-sea interaction. Without the gusts, fresh rain water stratifies the upper ocean in a coupled column model, allowing SST to warm beneath convection, in contrast to observations.
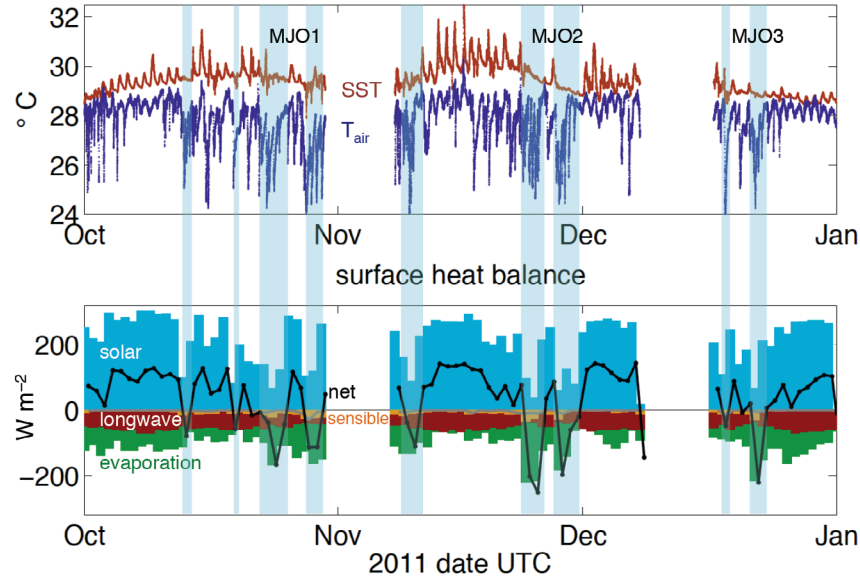

Figure 1. SST warms and cools on intraseasonal time scales, forced by variations in solar flux and evaporation related to convective anomalies indicated by MJOs.

Increased sea-air temperature difference and wind gusts locally double latent and sensible heat fluxes. Figure 3 shows the composite heat flux in the 2 hours about 222 cold pools identified by sudden temperature drops. Blue boxes show median covariance fluxes (numbers indicate length in minutes of the covariance window) and the dashed red line shows the median of all 222 events. Longer covariance flux windows resolve more of the increased flux after the front. The *mean* heat flux is 50% stronger indicating the positively skewed distribution of heat flux in the composite.
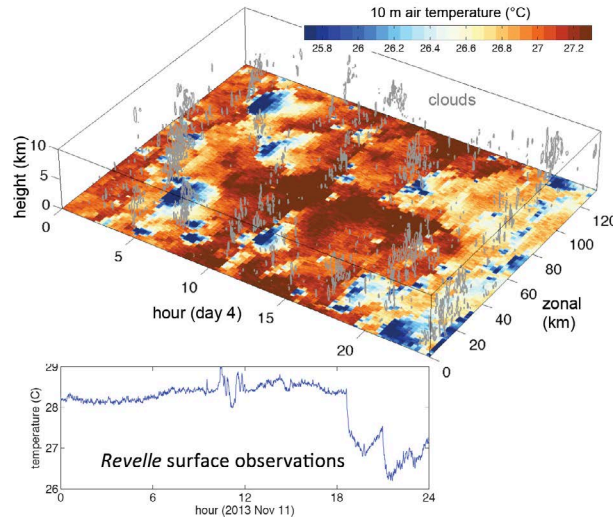
Figure 2. (a) LES time zonal-height slices of clouds (gray) over 10 m air temperature (shaded) match the character of (b) cold pools observed in LASP/DYNAMO.

Cold pools are denser than their surroundings, but they are not density currents. Their quick recovery (10-30 min) show that most are shallower than 50m. Therefore the gusts at their fronts must be driven by momentum advection rather than hydrostatic pressure.
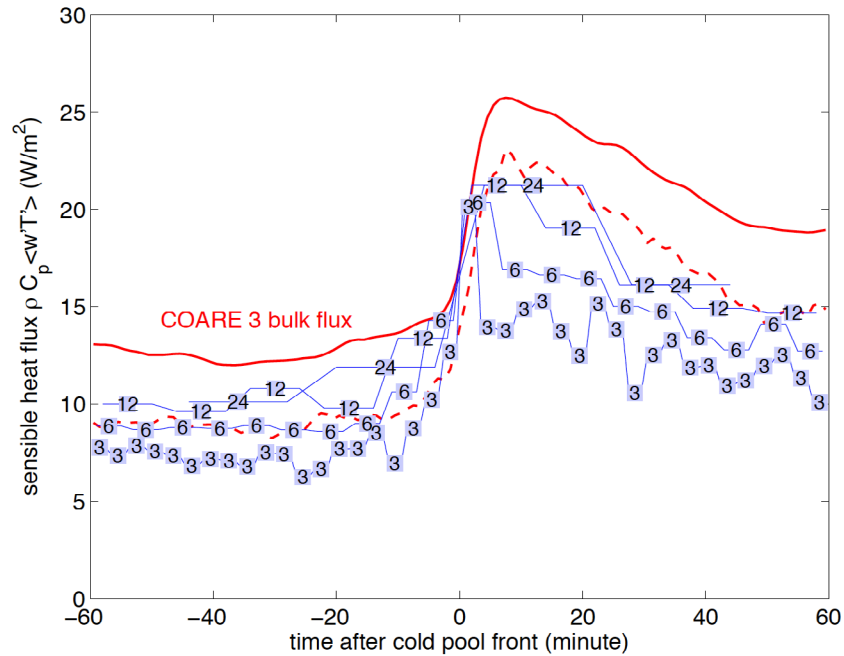

Figure 3. Wind gusts are observed to double the turbulence stress and heat flux for about 30 minutes after cold pool fronts. COARE median heat flux agrees with covariance fluxes.

These mesoscale structures that enahnce the surface winds and heat fluxes are preferentially embedded in the convective phases of the MJO. Figure 1 shows lower surface temperature and stronger sea-air temperature difference during convective MJO phase.

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Large-Eddy Simulation Results

Simulations are initialized with two different soundings taken from the LASP/DYNAMO experiment; one based on the average conditions during the entire cruise and the second altered by lowering specific humidity above 5000 m to represent conditions prior to the November 2011 MJO event. Horizontal domain size in both cases is set to 268.8 km x 268.8 km, with a maximum height of 22 km. Model spin up is conducted using a coarse resolution of 600 m, which is then improved to 300 m after the model reaches quasi equilibrium. Vertical resolution is ~20 m near the surface, increasing to 150 m until reaching the tropopause where the grid is gradually stretched to 700 m. The total grid size is 896 x 896 x 100 in the fine resolution case.
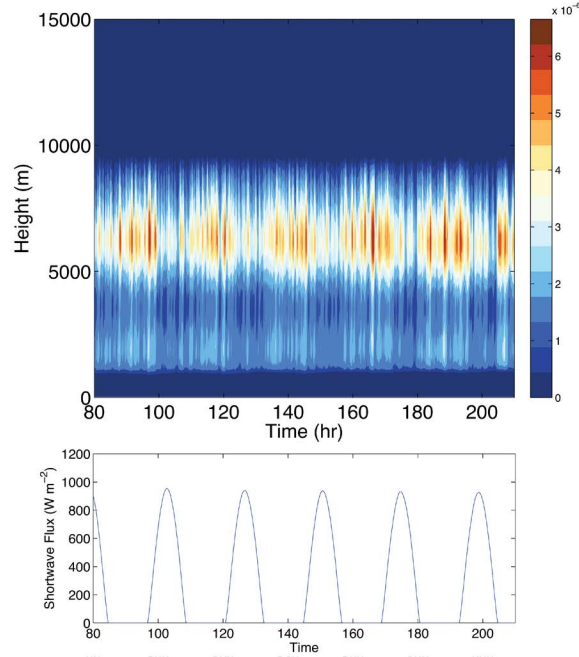

Figure 4. Horizontally averaged cloud water content from the low resolution simulation (top) and surface shortwave radiation (bottom).

Plots of the average cloud water content shown in Figure 4 show that cloud systems exhibit a diurnal signal with a clear maximum in the early morning hours before sunrise. Over simulation time period, convective pulses tend to persist for longer periods of time. This characteristic represents larger-scale cloud clusters that become the dominant feature as the simulation progresses.

The structure of convective systems is more clearly shown by a horizontal plane view of the cloud albedo and surface latent heat flux (Figure 5). At this time a single strong group of convective cells has formed near the center of the domain and has produced a cold air outflow that is moving southward generating a maximum in the latent heat flux. Other remnant cold pools are also present as shown by linear regions of enhanced flux. New cells are developing along the southwest facing leading edge of the cold air outflow where moisture convergence is a maximum. Surface fluxes north of the strong cell are suppressed by weaker winds and suppressed boundary layer eddies.

Simulations show that convective clusters develop along cold air outflows with new cells forming at the intersection of old outflow boundaries. New cells often form when the cold pool recirculates through the periodic model domain, limiting the use of the model in determining maximum cluster size. Further work is planned with larger domains to examine if this process continues up scale.

The simulated ocean response to convection suggests that changes in SST are strongly controlled by wind stirring from cold air outflows. As shown in Figure 2, outflow winds are able to generate fluxes 10-20 times higher than the background wind (~ 2 m s^{-1}) generated flux. Consequently, enhanced stratification from freshwater rain flux is typically short lived and there does not appear to be a significant relationship between SST variability and rain. The role of cold pools in the coupled simulation is made clear by conducting an experiment without evaporative cooling in the cloud microphysics package. Cold pools in this situation are not produced and we find a much stronger SST response for regions of high precipitation.

Differences in convective organization are also seen between the dry and moist soundings with clusters forming more quickly in the dry case. Cold pools in the dry case are more intense because of increased evaporative cooling, which most likely leads to enhanced cluster development.
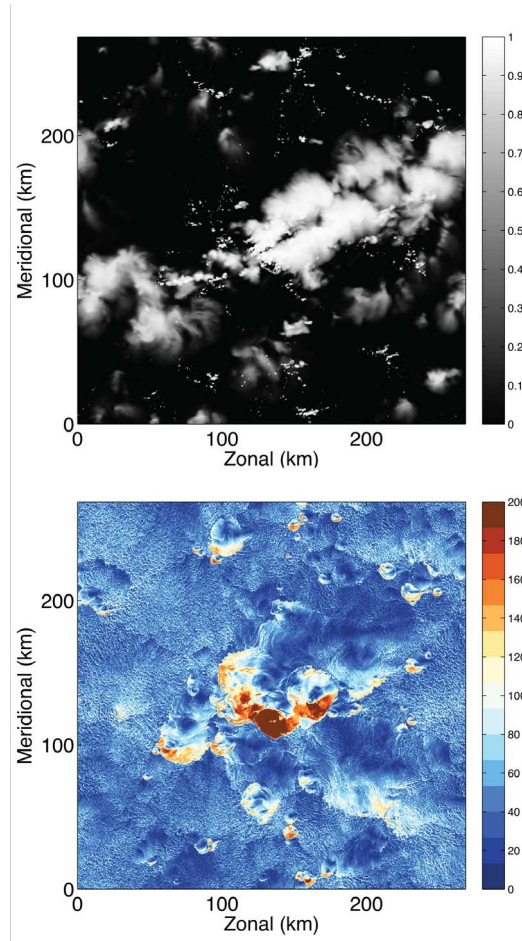

Figure 5. Simulated cloud albedo (top) and suface latent heat flux (W m^{-2}, bottom) at hour 246

RELATED PROJECTS

This project is part of the Indian Ocean Air-Sea DRI and is a part of DYNAMO. A related DYNAMO National Science Foundation project entitled "DYNAmics of the Madden-Julian Oscillation / Analysis of subsurface fluxes with coupled large-eddy simulation models" will provide a significant ocean component not proposed in the current project.